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Interferometry and the Fundamental Properties of Stars

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Abstract. For many decades the determination of accurate fundamental parameters for stars (masses, radii, temperatures, luminosities, etc.) has mostly been the domain of eclipsing binary systems. That has begun to change as long-baseline interferometric techniques have improved significantly, and powerful new instruments have come on-line. This paper will review the status of the field, and in particular how the knowledge of precise stellar properties helps us understand stars. Main-sequence stars similar to the Sun are by far the best studied, but much remains to be done for other kinds of objects such as early-type as well as late-type stars including brown dwarfs, evolved stars, metal-poor stars, and pre-main sequence stars. Progress is illustrated with several examples of how interferometry has contributed significantly in some of these areas.

1. Introduction

The determination of the fundamental properties of stars, i.e., their masses, radii, effective temperatures, luminosities, etc., is a classic discipline in Astronomy that goes back more than a century. To many, this area of work may not seem as appealing or fashionable as other topics such as cosmology and extrasolar planet research, which seem to garner most of the attention these days. It is worth keeping in mind, though, that there are few areas in modern Astrophysics that do not rely to some extent on our knowledge of the basic properties of stars, and this includes cosmology and extrasolar planets.

Perhaps the most important application of precise measurements of the mass and other stellar characteristics is to improve our understanding of stellar structure and stellar evolution, by comparing the observations against predictions from current models. Numerous examples of such comparisons may be found in the literature (see, e.g., Pols et al. 1997; Lastennet & Valls-Gabaud 2002; Hillenbrand & White 2004), and have shown that while our knowledge of the physics of stars appears to be in reasonably good shape for solar-type stars, the agreement in other parts of the H-R diagram is not as good. More practical applications include the estimate of the total mass in stellar clusters making use of the well-known mass-luminosity relation determined empirically from observations of binary systems (the only ones allowing a dynamical measurement of the mass). Binary stars with well-determined properties serve also as valuable distance indicators, not only in the Milky Way but also in other galaxies (SMC, LMC, M31, M33), and have become an important tool for establishing the large-scale structure of the Universe.

In recent years the field of extrasolar planets has highlighted the importance of understanding stars. For transiting exoplanets, for example, in which the observables

are the transit light curve and typically also a spectroscopic radial-velocity curve, the masses and radii of these objects cannot be determined independently of those of the parent star. Even if the inclination angle is precisely known in these cases, the value of the planet mass derived from the spectroscopic orbit scales as $M^{2/3}$, where M is the mass of the host star. Similarly, the measurement of the depth of the transit events does not immediately yield the radius of the planet, but only the *ratio* between the planet radius and the stellar radius. It is essential to know the properties of stars in order to learn about planets. Thus, in this era of deep questions about the possibility of life on other worlds, and the frequency of planets like our own in the Universe, stellar Astronomy has become relevant again.

In this review I will outline the techniques applied to measure stars, and the status of the field of fundamental stellar parameter determination. I will also illustrate some of the contributions from long-baseline interferometry, which is the subject of this Workshop.

2. Methodologies

The observational and analysis procedures for determining basic stellar properties are well known, and I will only summarize them briefly here, pointing out some of their advantages and limitations.

Masses. A common misconception is that measurements of a binary system of any type automatically yield dynamical masses for both components. This is of course not true. Only binaries with certain kinds of measurements allow the individual masses to be determined without assumptions. Historically the most precise mass determinations have come from double-lined spectroscopic binaries that undergo eclipses. Note that *single-lined* eclipsing binaries *do not* yield the individual masses; radial velocities need to be measured for both components in order for this to be possible, unless one is willing to *assume* a value for the mass of one of the stars. And of course, without eclipses neither single- nor double-lined spectroscopic binaries allow the absolute masses to be calculated; only a lower limit on the secondary mass can be derive in the first case, and lower limits for both stars in the second case.

Another common way in which masses are derived when eclipses do not occur is in double-lined spectroscopic binaries that are spatially resolved, and in which the astrometric orbit of the secondary relative to the primary is determined interferometrically or by other means such as direct imaging (for a review, see Torres 2004). In this case one can calculate not only the absolute masses of both stars, but also the “orbital parallax” from the ratio between the (de-projected) linear semimajor axis from spectroscopy and the angular semimajor axis from astrometry. This added bonus makes double-lined astrometric-spectroscopic binaries particularly useful because they allow the individual luminosities to be computed from the apparent brightness of the stars; thus, both the masses and the luminosities can be known in these cases, independently of any models. The high precision of long-baseline interferometric observations of some binaries has yielded very precise distances and luminosities for stars, in addition to the masses. If radial velocities are measured for only one of the components, however, then an additional piece of information is needed to obtain the individual masses. This usually involves *independent* knowledge of the trigonometric parallax, such as from the Hipparcos mission (Perryman et al. 1997; van Leeuwen 2007). If only the

relative astrometric orbit is known, and no velocity measurements are available, individual component masses cannot be obtained without assumptions. In these cases one can only infer the *total* mass (from Kepler's third law), provided the distance to the system is known.

Long-baseline interferometric measurements of binaries are usually relative in nature, and require radial velocities (of both stars) to be able to infer the masses. When the astrometric motion of each star can be measured separately against a background of reference stars, then spectroscopy is not needed at all to infer the masses of both stars. An example of such absolute astrometric measurements and mass determinations using the Fine Guidance Sensors on HST may be seen in the work by Hershey & Taff (1998).

Radii. Double-lined eclipsing binaries have been our main source of accurate absolute radii for stars. The solution of the light curves yields the individual radii in terms of the semimajor axis, and the spectroscopy provides the absolute scale. However, in recent years very precise radius measurements have also been possible with long-baseline interferometry (yielding angular diameters) combined with accurate parallaxes from the Hipparcos mission. This is discussed further below, in connection with low-mass stars. One difficulty that should be pointed out is that angular diameters are usually only available for single stars, and are typically very difficult to measure interferometrically in binary systems. This is unfortunate, as dynamical masses can only be measured in binaries. I will not discuss here the subject of asteroseismology, which can also provide an accurate measurement of a quantity closely related to the stellar radius which is the mean density of the star. Reviews on the power of asteroseismology for determining stellar properties can be found elsewhere in this Volume.

Temperatures. Interferometry enables the determination of effective temperatures for stars in the most fundamental way, through the well-known relation between the bolometric flux of a star as observed from the Earth ($f_{\oplus, \text{bol}}$), the temperature (T_{eff}), and the limb-darkened angular diameter (θ_{LD}). This relation is $f_{\oplus, \text{bol}} = \sigma T_{\text{eff}}^4 \theta_{\text{LD}}^2 / 4$, where the symbol σ represents the Stefan-Boltzmann constant. Flux measurements require observing the star at a range of wavelengths, and fitting the spectral energy distribution with some model. The dependence of the results on this model is minimal, however. More of these determinations have become available in recent years thanks to improvements in the precision of the interferometric angular diameters.

Other ways of determining stellar temperatures are less fundamental. For example, spectroscopic techniques rely heavily on model atmospheres, and do not work very well for cool stars, which display strong molecular features that the models still have difficulty reproducing in detail. A common way of inferring temperatures indirectly is through the measurement of a color index and the use of color-temperature calibrations (e.g., Casagrande et al. 2008, 2010). These are available in a variety of photometric systems. Much progress has been made recently in understanding the systematics that have affected these relations in the past, and remaining biases are now believed to be smaller than 100 K. Photometric temperatures are sensitive to reddening, however, so care is required with this approach.

Luminosities. In eclipsing binaries in which color indices on a standard system are available for both components, bolometric luminosities are easily obtained from the absolute radii and photometrically estimated temperatures through the Stefan-Boltzmann

equation, with the same caveat on the reddening as above. For single stars, the widely used Infrared Flux Method (IRFM) can provide both the angular diameters and the temperatures at the same time (see, e.g., Blackwell & Shallis 1977; Blackwell et al. 1979; Ramírez & Meléndez 2005). When combined with a measurement of the parallax, it is then possible to infer the luminosity. In practice luminosities are often derived from a measurement of the apparent brightness, a parallax (either trigonometric or “orbital”; see above), and bolometric corrections from standard tables. Because of the arbitrary nature of the zero point of these corrections, which many investigators often overlook, attention to this matter is required to ensure consistency (see Torres 2010).

Metallicities. When the goal is to use measured stellar properties (M , R , T_{eff}) to test models of stellar evolution, knowledge of the chemical composition of a star provides for a much more stringent comparison. Otherwise this becomes a free parameter that can be changed in the models so as to achieve the best fit. Metallicity is usually determined spectroscopically through a spectral synthesis approach or by measuring equivalent widths, although this is always more difficult in binary systems with composite spectra. As for the case of spectroscopically determined temperatures, poorly known molecular opacities in the atmospheres of cool stars make metallicity determinations problematic. Photometric calibrations for solar-type and also cooler stars are available as well (e.g., Holmberg et al. 2007; Twarog et al. 2007; Schlafman & Laughlin 2010), but spectroscopic determinations are preferable when possible.

3. Status of accurate mass and radius determinations for normal stars

Binary stars have been studied for more than two centuries, yet the number of eclipsing systems with accurate mass and radius determinations represents only a tiny fraction of the many thousands of systems known. An early review of the status of the field by Popper (1967) listed only two systems with absolute masses (but no radii) known to 3% or better, among many others with more poorly determined properties. An update 13 years later increased the tally of well known systems to seven, this time including the radii (Popper 1980). Starting in the 1970’s, efforts by the Danish group led by J. Andersen brought the number up considerably, and by the time of the next major review on the subject a total of 45 binaries (90 stars) had masses and radii with relative errors of 3% or better (Andersen 1991). Since then significant improvements have been made in both the observational and the analysis techniques. As a result, the number of well studied systems has more than doubled to 95 in the most recent review (94 eclipsing systems, and α Centauri; Torres et al. 2010), which for the first time includes an extragalactic binary.

Figure 1 shows the distribution of these systems as a function of stellar mass (filled circles), with the relative errors in mass and radius plotted on the vertical axes. In both panels the slightly rising lower envelope toward higher masses is mostly due to increasing difficulties with the spectroscopic analysis in early-type systems, caused by strong winds and other complications in their spectra.

Long-baseline interferometry has been making steady progress over the last decade or so, and now contributes significantly to the list of high-quality mass measurements. In fact, in addition to the eclipsing binaries, the review by Torres et al. (2010) lists some two dozen interferometric binaries in which both components have mass determinations that are also good to 3% or better. These are shown with open circles in the

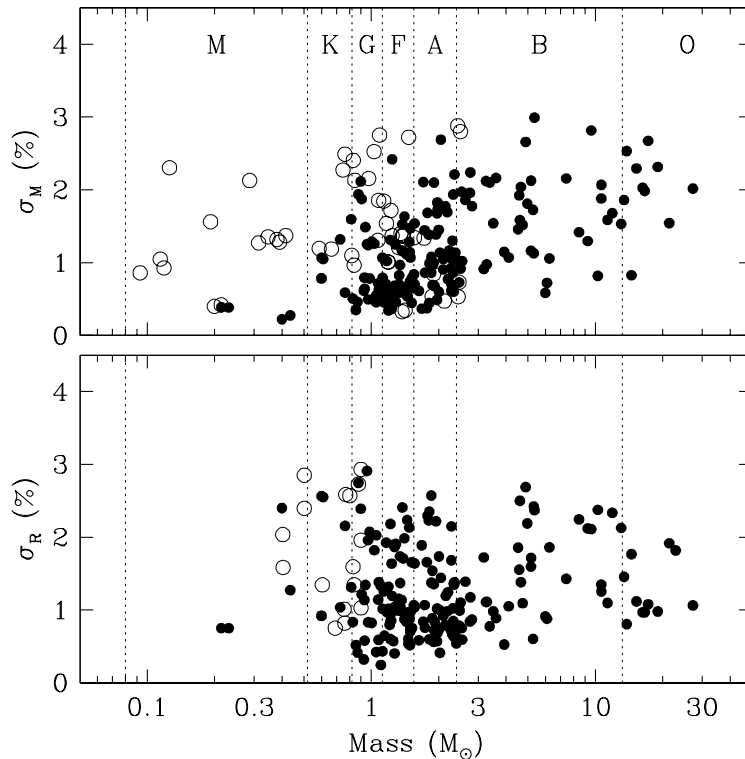


Figure 1. Stellar mass and radius uncertainties as a function of mass for the 94 eclipsing binary systems plus α Cen (filled circles) with relative errors smaller than 3%, from Torres et al. (2010). Open circles in the top panel correspond to additional systems with mass determinations from long-baseline interferometry (see text). Open circles in the bottom panel correspond to stars with angular diameter measurements from interferometry (but with no corresponding dynamical masses, which are estimated here using the mass-luminosity relations of Delfosse et al. 2000). Spectral types are indicated along the top.

top panel of Figure 1. While there are very few well-studied eclipsing binaries among the later type stars, interferometry is seen to be quite complementary and has added a significant number of K- and M-type stars. The downside, as mentioned earlier, is that these interferometric mass measurements are not accompanied by the corresponding radius measurements, so are generally of more limited value for testing models of stellar evolution.

4. Contributions of long-baseline interferometry

In this section I describe a few selected areas in which interferometry has made especially interesting contributions to the determinations of the global properties of stars, and/or has provided useful tests of stellar theory. Other articles in these Proceedings describe additional stellar quantities that interferometry is particularly well suited to measure.

4.1. Stellar radii and the discrepancies with models for low-mass stars

As advanced as our current knowledge is of stellar structure and stellar evolution, there are plenty of indications that our understanding of stars is far from complete. A prominent example is in the area of low-mass stars. For nearly four decades there has been mounting evidence that the measured radii of these stars are larger than theory predicts by up to $\sim 10\%$, and also that their effective temperatures are cooler than anticipated by up to $\sim 5\%$. Early indications of these anomalies were reported by Hoxie (1973) and Lacy (1977), and were strengthened by Popper (1997), Clausen et al. (1999), and others. More recent highly accurate determinations of the masses, radii, and temperatures in low-mass eclipsing binaries such as YY Gem, CU Cnc, GU Boo, CM Dra, and others have now removed all observational ambiguity (Torres & Ribas 2002; Ribas 2003; López-Morales & Ribas 2005; Morales et al. 2009). Enlarged radii have been confirmed in a number of additional systems, although I note that these measurements are not all equally reliable. Many of the mass-radius diagrams seen in the recent literature show considerable dispersion, making the picture rather confusing. Some of this scatter may be due to real differences between systems, but it is likely that the published uncertainties for many of these binaries are unrealistically small, and do not account for systematics. In particular, few of these studies document any tests to investigate the effects of spots, which are prevalent in late-type stars (see, e.g., Morales et al. 2008; Windmiller et al. 2010; Morales et al. 2010), or offer external constraints as a check on the light curve solutions.

In any case, it is clear that current stellar evolution models underestimate the radii of late-type stars, and overestimate their effective temperatures. The effect is believed to be due to chromospheric activity in close binary systems. Indeed, most of the stars that show this anomaly are in short-period binaries, where strong tidal forces drive the components into spin-orbit synchronization (rapid rotation). As a result, these systems often display variability due to spots, X-ray emission, and spectral signatures of activity such as Ca II H and K emission, H α emission, etc. (see, e.g., López-Morales 2007). While there is in fact a theoretical understanding of the impact of activity on the radii and temperatures of low-mass stars (D’Antona et al. 2000; Mullan & MacDonald 2001; Chabrier et al. 2007, and others), these effects are yet to be incorporated into publicly available stellar evolution models.

An obvious action item on the part of observers is to now focus on long-period low-mass eclipsing binaries, in which the stars might be expected to rotate more slowly and to therefore be less chromospherically active. These could show better agreement with theory, thereby supporting the idea that activity is the culprit. Although a few such systems have been found from the ground, they are generally rare and challenging to study. Space missions such as CoRoT and *Kepler* are anticipated to provide many examples of long-period eclipsing binaries with late-type components, although they may be faint.

This is an area where long-baseline interferometry has already made and continues to make important contributions. While it may be difficult to find suitable long-period eclipsing binaries with late-type components in order to measure their radii, single stars of late spectral type are plentiful, and more easily studied. In recent years several groups (PTI, VLTI, CHARA) have measured very precise angular diameters for late-type stars with known parallaxes (Lane et al. 2001; Pijpers et al. 2003; Ségransan et al. 2003; Di Folco et al. 2004; Berger et al. 2006; Kervella et al. 2008; Baines et al. 2008; Boyajian et al. 2008; Demory et al. 2009, and others). In some cases the precision ob-

tained for the absolute radii is quite competitive with that achieved in eclipsing binary systems. And while there are no dynamical masses to accompany the interferometric radii, it is usually possible to make use of near-infrared mass-luminosity relations such as those by Delfosse et al. (2000) to infer sufficiently precise mass estimates for the purpose of placing the stars on the mass-radius diagram and comparing with theory.

Demory et al. (2009) have made such a comparison, and report finding that interferometrically measured stars (which are typically rotating slowly, and are thus presumably relatively inactive) do in fact agree with stellar evolution models much better than stars in eclipsing binaries, as one might expect. Other groups reach a different conclusion, however, so a final answer must await further interferometric observations (see Boyajian et al. 2010).

Stars with interferometrically measured radii good to better than 3% are indicated with open circles in the bottom panel of Figure 1. As was the case with the masses, interferometry is seen to be very complementary to the eclipsing binaries in providing accurate radii for the lowest-mass systems.

4.2. Properties of metal-poor stars

One of the areas in which stellar evolution models are most poorly constrained is that of stars with chemical compositions very different from the Sun, and in particular those that are metal-poor. Detached binary stars that are suitable for accurate mass and radius determinations and that have known metal-poor compositions are rare. Eclipsing binaries in globular clusters are of course obvious targets, but they tend to be faint and difficult to study. One of the best examples published recently is that of the variable V69 in 47 Tucanae (Thompson et al. 2010), with an adopted metallicity for the cluster of $[\text{Fe}/\text{H}] = -0.70$ and α -element enhancement of $[\alpha/\text{Fe}] = +0.4$. Possibly the most metal-poor field eclipsing binary with accurately known masses and radii is V432 Aur (Siviero et al. 2004), with a measured $[\text{Fe}/\text{H}] = -0.60$. Other binary candidates in clusters with much lower metallicity are known (e.g., Thompson et al. 2001; Kaluzny et al. 2006, 2008), but their properties are not yet determined sufficiently accurately to be useful for testing models.

Once again long-baseline interferometry has an advantage, as it does not require the binary to be eclipsing in order to determine the dynamical masses of its components. A good example is HD 195987 (Torres et al. 2002), a nearby high proper motion field star with $[\text{Fe}/\text{H}] = -0.50$ and $[\alpha/\text{Fe}] = +0.36$, in which the masses of both stars were determined to better than 2% based on interferometric measurements with the PTI.

4.3. Properties of evolved stars

Binary stars with components in rapid phases of evolution (giants or subgiants) that are sufficiently detached so that they don't interfere with each other and that are suitable for high-precision mass determinations are also quite rare. Only a handful of eclipsing systems of this type are known, including AI Phe, TZ For, and the system OGLE 051019.64–685812.3 in the LMC (Andersen et al. 1988, 1991; Imbert 1987; Pietrzyński et al. 2009). Astrometric-spectroscopic systems that are amenable to interferometric studies are somewhat more common, but not many have yielded the precision needed for testing models. One such example investigated with the PTI is HD 9939 (Boden et al. 2006), in which the primary star appears to be traversing the Hertzsprung gap.

Perhaps the most prominent example of a pair of giants studied interferometrically is Capella (α Aur, G8 III + G0 III), which is in fact the very first system studied with this technique (Anderson 1920; Merrill 1922) using the original Michelson interferometer on Mount Wilson. Despite its century-long observational history, the properties of Capella have been surprisingly difficult to pin down, particularly the masses. The recent study by Torres et al. (2009) made use of all available interferometric data (from COAST, Mark III, IOTA, and other instruments) combined with radial velocity measurements spanning more than 100 years, and derived component masses with formal errors smaller than 0.7%. Capella is unique among the evolved systems in the amount of information available for the system, which in addition to the masses includes the absolute radii (from angular diameter measurements), spectroscopic effective temperatures, independently determined luminosities (based on the accurate orbital parallax), projected rotational velocities $v \sin i$, rotational periods from chromospheric activity indicators, and importantly, the chemical composition. The latter includes not only the overall metallicity [m/H], but also the carbon isotope ratio $^{12}\text{C}/^{13}\text{C}$ for the primary, and the lithium abundance and carbon-to-nitrogen ratios for both stars. The last three quantities are sensitive diagnostics of evolution, and change drastically for giants as a result of the deepening of the convective envelope during the first dredge-up.

The secondary component is crossing the Hertzsprung gap, while the primary is believed to be in the longer-lived phase in which it burns helium in the core (“clump giant”), although the observational evidence for this is still somewhat controversial. With so much information one would think that the precise evolutionary state of the primary ought to be very well established. However, the study by Torres et al. (2009) concluded that current models of stellar evolution are unable to fit all observational constraints simultaneously for both stars, at a single age. Very recently a new spectroscopic study by Weber & Strassmeier (2011) has yielded masses with even smaller formal errors of about 0.3%, but which differ from the previous values by 4% and 2% for the primary and secondary, respectively. Thus, the last word is yet to be said on the evolutionary state of the primary and the ability of current models to match all observational constraints; Capella is not yielding its secrets so easily.

4.4. Interferometry and the Pleiades distance

Soon after the publication of the Hipparcos results on the trigonometric parallaxes of $\sim 118,000$ stars, a controversy ensued regarding the distance to the Pleiades cluster. Based on measurements for 55 member stars observed by the satellite in this cluster, van Leeuwen (1999) reported an average distance of 118.3 ± 3.5 pc, which was in disagreement with results based on the widely used method of main-sequence isochrone fitting. That technique gave significantly larger values (e.g., 131.8 ± 2.5 pc; Pinsonneault et al. 1998). The difference of $\sim 10\%$ corresponds to about 1 mas in the average parallax of the cluster, or 0.23 mag in the distance modulus. The prospect of systematic errors at this level in the Hipparcos parallaxes was a rather serious concern and was difficult to accept for some, particularly since no such problem had been detected in the parallaxes of other open clusters including the Hyades. But the possibility that stellar evolution models, which had worked so well in the past, could be off by as much as 0.23 mag was equally worrisome, and could have wide-ranging implications for much of Astrophysics.

A partial solution to the problem came from several different fronts, one of them involving long-baseline interferometry of a binary system in the cluster. Zwahlen et al.

(2004) made use of interferometric observations of the bright 291-day B8 III binary star Atlas (27 Tau, HD 23850) collected with the Mark III interferometer and with NPOI, and for the first time measured also radial velocities of both components (only the primary had been measured previously), with which they derived the spectroscopic orbit. From these measurements they obtained the orbital parallax, corresponding to a distance of 132 ± 4 pc, supporting the isochrone fitting value. Additional support for this larger distance came from another binary in the cluster, the double-lined eclipsing system HD 23642, in which a determination of the absolute properties (particularly R and T_{eff} , and therefore L) led to a largely model-independent distance estimate (Torres 2003; Munari et al. 2004; Southworth et al. 2005; Groenewegen et al. 2007). Further support came from directly measured trigonometric parallaxes of three cluster members using the Fine Guidance Sensors on HST (Soderblom et al. 2005). A re-reduction of the Hipparcos data (van Leeuwen 2007) removed correlated errors that affected the original parallaxes, and reduced the discrepancy somewhat (giving a distance of 122.2 ± 2.0 pc), but not completely. The remaining difference has not been explained; it may have something to do with the depth of the cluster and the particular location of the stars studied, or other unrecognized systematic biases (for a review on the subject, see Perryman 2009).

4.5. Towards higher precision in binary masses

Typical uncertainties in the absolute mass determinations for the best studied eclipsing binaries are 1–2%, with a few systems reaching values as low as a few tenths of a percent. Recent work by Konacki et al. (2010) has attempted to push these limits even further, for selected double-lined spectroscopic-interferometric binaries (see also earlier work focusing on eclipsing binaries by Lacy 1992). The improvements are based in part on a spectroscopic technique borrowed from the exoplanet search programs for measuring very precise radial velocities of stars, applied here to composite spectra rather than to single-lined spectra (Konacki 2005). The method uses an iodine cell in front of the spectrograph slit to track spectrograph drifts and changes in the point-spread function that normally lead to systematic errors in the radial velocities (Marcy & Butler 1992; Butler et al. 1996). The precision achievable in the velocities for these double-lined systems is a few tens of m s^{-1} . Interferometric orbits for the binaries in the work of Konacki et al. (2010) were obtained using the PTI, with emphasis placed on those with nearly edge-on orbits. This maximizes the precision in the masses, given that in astrometric-spectroscopic systems the mass M is inversely proportional to $\sin^3 i$, where i is the inclination angle of the orbit:

$$\begin{aligned} M_1 \sin^3 i &= P(1 - e^2)^{3/2} (K_1 + K_2)^2 K_2 / 2\pi G \\ M_2 \sin^3 i &= P(1 - e^2)^{3/2} (K_1 + K_2)^2 K_1 / 2\pi G . \end{aligned}$$

In the above expressions P is the orbital period, e the eccentricity, and K_1 and K_2 are the semi-amplitudes of the radial velocity curves. For example, if the inclination angle of the orbit is 10° (nearly face-on) and one wishes to obtain a relative precision of 3% in the masses, the precision in i must be at least 0.1 in order for the astrometry not to dominate the error budget. Such a small error in i can be difficult to achieve. However, if the binary has an inclination of 87° (i.e., almost edge-on), one can get away with an uncertainty in i as large as 10° (100 times worse than before), and still be able to measure masses to 3% precision.

Two of the binary systems studied by Konacki et al. (2010) reach record precision in the masses of the components. The formal errors for the F-star system HD 123999 are 0.20%, while for HD 210027 they are as low as 0.066% (the smallest error obtained for any normal star). Orbital parallaxes for these two binaries were also obtained to very high precision, the uncertainties being only 44 and 32 micro arc seconds, respectively ($\sim 0.15\%$). The precision of the masses for HD 210027 rivals that of the best known determinations in double neutron star systems, measured by radio pulsar timing. Konacki et al. (2010) expect that other binary stars may yield similar precisions if they are selected to have favorable properties, including masses between $0.5 M_{\odot}$ and $1.5 M_{\odot}$ so that they have sufficiently numerous and sharp spectral lines, periods between 3 and 23 days, inclination angles between 85° and 90° , uncertainties in i no larger than 0.3° , and errors in the radial-velocity semi-amplitudes under 31 m s^{-1} .

5. Final remarks

Long-baseline interferometry continues to make important contributions to our knowledge of accurate masses and other fundamental properties of stars. However, it is a scarce resource: there are not many of these instruments in the world, and it is generally a very difficult technique that requires specialized skills. It also has significant limitations regarding sensitivity (although this is improving, and there are high hopes for the Magdalena Ridge Observatory Interferometer currently under construction). Consequently, it is important to use these facilities wisely.

Astronomy would benefit the most from applications of interferometry to objects of special astrophysical interest, rather than those that are easiest to observe. In the field of accurate fundamental parameters of stars, there are several areas of the H-R diagram where much work remains to be done in order to constrain models of stellar evolution. This includes low-mass stars, high-mass stars, evolved stars (giants and subgiants), pre-main sequence stars, and stars of non-solar metallicity. As described above for some of these categories, constraints on the models are either very scarce, or problems with theory have already been identified that require additional observations to help guide theorists toward a better understanding of the discrepancies. When considering recent improvements in observational and analysis techniques, prospects are good for significantly increased precision in fundamental stellar properties.

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